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Sustainable Materialisation of Responsive Architecture

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Abstract: Natural organisms which employ inherent material properties to enable a passive dynamic response offer inspiration for adaptive bioclimatic architecture. This approach allows a move away from the technological intensity of conventional "smart" building systems towards a more autonomous and robust materially embedded sensitivity and climatic responsiveness. The actuation mechanisms of natural responsive systems can be replicated to produce artificial moisture-sensitive (hygromorphic) composites with the response driven by hygroexpansion of wood. The work presented here builds on previous research on lab-scale material development, to investigate in detail the applicability of wood-based hygromorphic materials for large-scale external applications. The suitability of different material production techniques and viability of potential applications is established through a detailed programme of experimentation and the first one-year-long durability study of hygromorphic wood composites in full weathering conditions. These results provide the basis for the design of an optimised responsive cladding system. The opportunities and challenges presented by building integration and architectural functionalisation of responsive wood composites are discussed based on a hierarchy of application typologies including functional devices and components, performance-oriented adaptive systems, the value of aesthetic and spatial experience and place-specific contextual integration. The design of the first full-scale building application of hygromorphic wood composites is presented.

Keywords: hygromorphic wood composite; durability; fabrication; biomimetic design; adaptive facade; sustainable architecture; passive building design

1. Re-Shaping Adaptive Architecture with Responsive Wood Composites

1.1. Ecologically Embedded versus Technologically Imposed Response

The accepted notion of a modern building is inextricably connected with the expectations of permanence and stability from both the structure and the interior climate, defying the natural variations of the external environment. In this context, a conventional building envelope is given the role of a barrier between the controlled interior space and transient outdoor conditions [1]. In contrast to traditional vernacular architecture, which has commonly been designed to employ the local climatic conditions, such as daylight and solar thermal radiation [2–4], modern buildings, often featuring extensively glazed facades, tend rely heavily on artificial heating, ventilation and air conditioning (HVAC) to maintain the desired interior comfort [5,6]. This overreliance on active (i.e., energy-dependent) building systems impacts energy performance of buildings during their operation, which accounts for approximately 80%–90% of the total energy consumed during their lifecycle [7,8].

The implementation of adaptive building technologies capable of real-time automated response to changeable environmental and operating conditions provides a possibility of improving a building's energy efficiency and facilitating enhanced occupant comfort [9,10]. This can be achieved by means of increasing the synchronisation and automation of the existing active systems [11] to optimise their performance and through incorporation of additional dynamic features, such as automated louver shading [12], that reduce the need for actuation of artificial lighting and HVAC. The intelligent climatically responsive behaviour of contemporary adaptive architecture is usually enabled by the application of separate mechanical and electrical components performing the sensing, processing, controlling and actuating functions [9,13]. Jean Nouvel's Institut du Monde Arabe, one of the earliest and most well-known buildings equipped with kinetic cladding, exemplifies this techno-centric design approach. Its cladding consists of series of 30,000 motor-controlled mechanical apertures designed to regulate the passage of light through the south façade [14]. The intricate arrangement of the openings imitates traditional Arabic Mashrabiya patterns, however, due to multiple mechanical failures and prohibitive maintenance costs, the operation of the system was abandoned soon after the building was completed in 1987 and is currently inactive [15]. Advancements in computational technologies and development of new materials have enabled de-coupling the response of cladding elements and improved robustness and adjustability of increasingly complex kinetic facades in recent projects, such as Al Bahr Towers in Abu Dhabi [12] and Media-TIC building [16] in Barcelona. Although the movement of the façade elements in these projects is electrically actuated and therefore these systems remain energy-reliant, they allow a significant reduction in the total energy consumption of the buildings [12,16]. However, the implementation of technologically-intensive smart architecture beyond the scope of landmark projects remains challenging due to its high cost and complexity [5].

The benefits of high-performance high-tech intelligent building technologies and zero-energy low-tech passive design can be combined in adaptive systems where the response is implemented by smart materials with embedded sensitivity to climatic stimuli [5,13,16]. The inspiration for material fabrication techniques and response mechanisms, which can be employed for this "hybrid" design approach, can be drawn from biological systems that function reliably and autonomously whilst minimizing resource usage [16,17].

Examples of such natural responsive systems include plant species that have evolved functional mechanisms of repeated moisture-induced shape morphing enabled solely by inherent hygroscopic properties and intricate hierarchical structure of their tissues. For instance, opening of seed-producing scales of conifer cones in a dry environment (Figure 1B) actuates the dispersal of ripe seeds ensuring favourable conditions for their germination [18]. This mechanism results from the bilayered structure of the scales which consist of cells with differing orientation of stiff cellulose microfibrils (CMFs), exhibiting large transverse and small longitudinal swelling and shrinkage (hygroexpansion) [19–21]. The anisotropic dimensional changes of CMFs are translated into differential hygroexpansion of the scales' layers which results in bending. The response of conifer cones is reversible and repeatable over many cycles even after the seeds are released and the tissues of the scales are biologically dead [13].

The ability to convert relatively small unidirectional dimensional changes into geometrically amplified movement permitted by the bilayer principle is also observed in a number of other natural systems, such as wheat awns [22], orchid tree seedpods [23] (Figure 1A), seed capsules of ice plants [24] and stems of spikemoss [25]. This principle can be adopted to produce artificial materials with programmable reversible moisture-induced response (hygromorphs) consisting of hygroscopic active layers, and passive layers, which provide constraint to planar hygroexpansion and force the composites to bend or twist, depending on the orientation of the layers (Figure 1). The development and potential application of hygromorphic materials in adaptive building skins provides opportunities for design of passively responsive bioclimatic architecture that is in constant synchronization with variable levels of atmospheric humidity and ambient moisture.

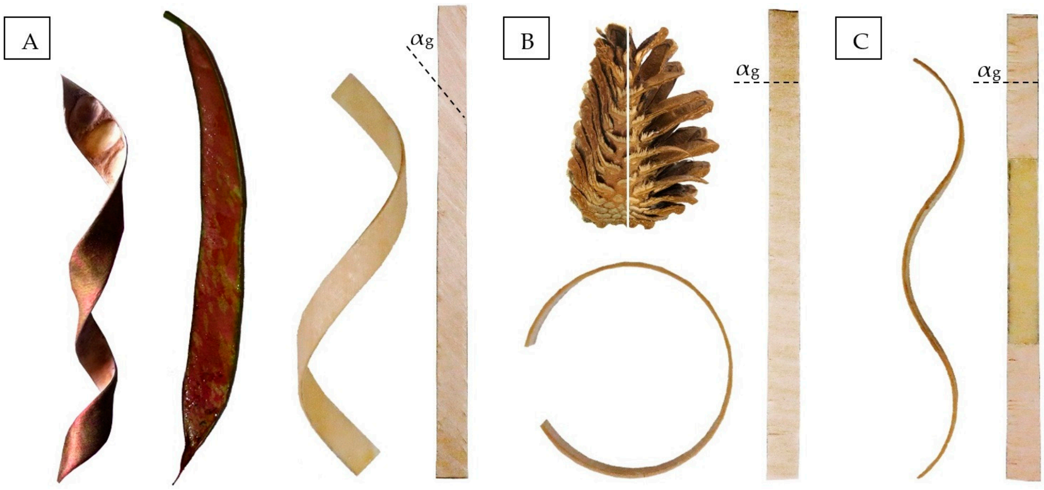

Figure 1. Examples of possible shape transformations of bilayered hygromorphic wood composites analogous to natural responsive systems. In addition to bending (**B**), local curvature changes can be converted into a variety of more complex response forms, such as twisting (**A**), achieved by adjusting the direction of wood grain in the active layer (α_g), and sinusoidal curve (**C**), enabled by alternate arrangement of the layers.

1.2. Wood versus Synthetic Active Layers

One of the main challenges for the development of hygromorphs suitable for building integration is how to scale up their size and mechanical strength to meet the requirements of large-scale applications, whilst retaining sufficient responsiveness [26]. The fulfilment of these criteria depends on the ability of the active layer to produce substantial hygroexpansion and generate enough force to drive the curvature changes of the composites. Wood is one of few natural hygroscopic materials which encompasses these characteristics and, in fact, greatly surpasses the combination of strength and magnitude and speed of moisture-induced response achievable with many synthetic alternatives [27], such as hydrogels [23], electro-active and layer-by-layer deposited hygroscopic polymers [28,29] and bacterial spores [30]. This points to good potential for application of wood for active layers of large-scale hygromorphs.

In the last decade, rapid advancements in material fabrication technologies have enabled the production of hygromorphic materials with synthetic active layers mimicking the natural structure of wood. This can be achieved by embedding oriented natural or synthetic cellulose-rich fibres within a hot-pressed [31] or 3D printed [32] polymer matrix. The main advantages of this approach are more consistent material properties and the ability to adjust the direction of the fibres within a single piece of material. However, the response speed of the resulting composites is reduced due to limited hygroscopicity of polymer-coated fibres [32]. In contrast, wood as a functional tissue of trees is naturally provided with multiple passageways for water adsorption and transport. In addition, it exhibits a pronounced orthotropy in many of its properties, including hygroexpansion [33], which helps prevent the undesirable effects of double curvature observed in composites with homogenous volumetric active layer expansion [34]. The ability to choose an active layer from a wide range of commonly available wood species with different properties, and to select different orientations of cut, provides the opportunity to tune the hygromorphic response and tailor durability and appearance for particular applications [34]. The use of a widely available, naturally formed, biodegradable, moisture-responsive material with low embodied energy [35–38] as the functional component of the composites has potential to reduce their environmental impact and decrease the complexity of material fabrication compared to hygromorphs with synthetic active layers.

Earlier works on wood-based hygromorphs have primarily been focused on the investigation of the effects of material configurations (including the choice and orientation of the layers) on the responsive capacity of the composites in short-term lab tests [13,26,34,39], application of the knowledge about the material properties and behaviour for parametric design generation and modelling of responsive [40] and self-constructing [32] surfaces with complex geometries and construction of small-scale prototypes [41] and temporary architectural installations [39] showcasing the technology. Wide availability of the applicable components of wood-based hygromorphic composites and improved understanding of the principles for choosing their configurations [26,34] has made it possible to produce working responsive bilayers on low budget and without the need for sophisticated equipment, which is quite unique in the context of smart materials. This has been employed in several short academic and design projects [42,43]. However, the existing research on long-term durability of the materials and consistency of their response, necessary to substantiate the currently limited discussion of their potential applications, is scarce and the material fabrication techniques and response pre-programming methods, which can enable the desired robust and reversible response, have not been sufficiently investigated and described. This paper seeks to further the insights into these key areas.

2. Addressing Challenges in Design and Production of Hygromorphic Composites

2.1. Methods of Material Fabrication

The production of wood-based hygromorphic composites capable of withstanding the internal stresses and large changes in curvature resulting from differential hygroexpansion over multiple cycles of response without delamination, requires the selection of fabrication methods that simultaneously provide high strength, stiffness, flexibility and durability of the interfacial bond between the layers [34]. At the same time, negative effects of the bond on the response size and speed must be minimised. Four different methods of material fabrication have been tested, including gluing, mechanical fixing and spot-gluing of rigid passive layers and direct lamination of glass fibre- and bio-fabrics (Figure 2).

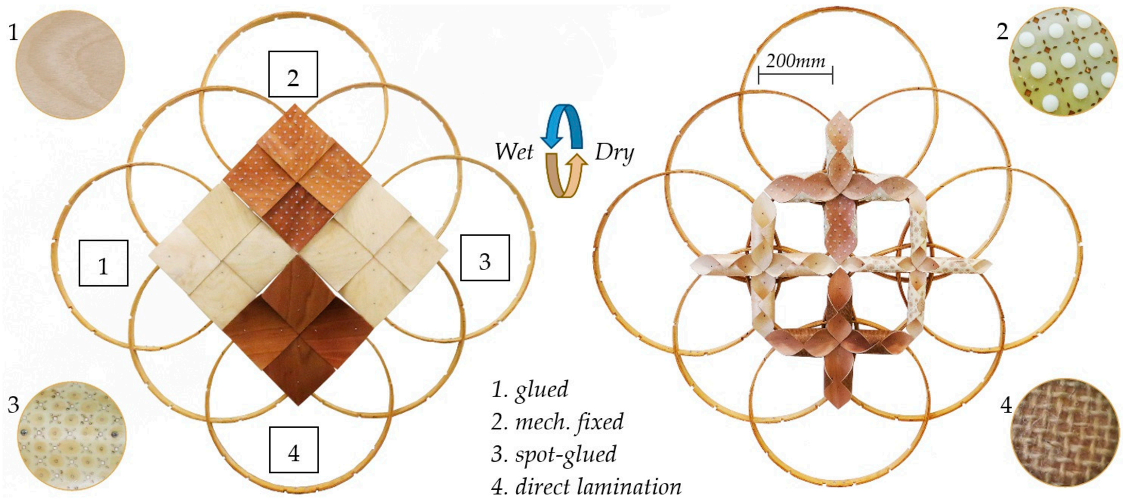

Figure 2. Demonstration prototype incorporating responsive panels with four different types of layer bonds. The passive layers are shown in the numbered circles (1—wood, 2 and 3—fiberglass and 4—jute fabric).

Gluing enables the production of a wide range of semi-synthetic hygromorphs with polymer, fiberglass or other synthetic passive layers and cross-grained laminates consisting of two wooden layers with different grain directions, such as in Figure 2 panel type 1. However, the choice of adhesive is limited due to stringent requirements for their water-resistance and mechanical properties when cured at high relative humidity and with substrates that have a high moisture content (MC). It has been experimentally established that only certain high-performance structural adhesives, which cure at room temperatures, can meet these requirements. These include selected two-part epoxies and polyurethane glues, such as Permabond ET5428 and Purbond HB-S309, respectively. However, none of the tested adhesives are effective when used with damp fully expanded wooden layers that have MC above ~30% (fibre saturation point, MCf). Once the adhesives come in contact with free water within the wood, their dissolution leads to decreased viscosity resulting in excessive penetration and staining of the active layer (Figure 3B) as well as loss of bond strength. Microscopic examination of the composites with glued layers has shown that the selected adhesives, which have dynamic viscosity ranging from 20,000 mPa.s to 35,000 mPa.s when applied in room conditions, only permeate the cavities of the wood cells that are adjacent to the glued surface with the rest of the active layer unaffected. This minimizes the unwanted reduction in the hygroscopicity of wood, which is the largest constraint for the use of low viscosity adhesives, such as cyanoacrylates, in the production of hygromorphs.

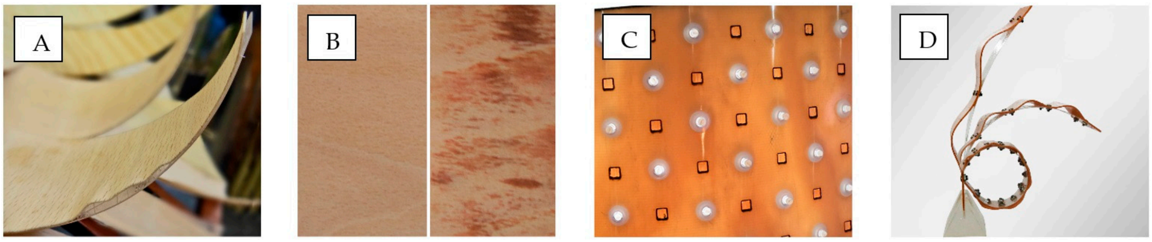

Figure 3. Issues addressed through improved methods of material fabrication: (**A**) delamination; (**B**) excessive penetration of adhesives or laminating resins into wood; (**C**) cracking of wood; and (**D**) local buckling of the layers between fixing points.

The need for a separate glue layer can be eliminated if a reinforcing fabric, such as interwoven glass fibres or natural bio-textiles, is laminated directly onto wood using liquid epoxy or bio-resin. Excessive soaking and starvation of the resin matrix can be prevented by pre-coating the active layer. However, due to precise timing required to ensure that the preliminary epoxy coating achieves just the right viscosity before lamination of the main passive layer, this extra production stage adds significant complexity to the fabrication. The use of bio-textiles, such as jute (Figure 2 panel type 4), flax or hemp, can reduce the embodied energy and cost of directly laminated passive layers in comparison to those with glass fibre reinforcement [38,44,45]. However, almost inevitable variations in the MC of the hygroscopic fibres can lead to their detachment from the resin matrix [31,46] and undesired changes in the properties of the passive layer. A common characteristic of the standard gluing and direct lamination production techniques is that the passive layer remains impermeable to water, and moisture exchange only happens through one side of the active layer which slows the response.

Mechanically fixing the composite layers guarantees that the issues of reduced hygroscopicity of wood and delamination (Figure 3A) are avoided. This method is well-suited for automated production and enables replacement and reuse or recycling of the layers. The passive layer can be perforated between the points of connection allowing moisture access through both sides of the composite. The integrity and quality of the riveted (Figure 2 panel type 2) or bolted connections is independent from the moisture content of the layers meaning that even wet wood can be used. Mechanical layer fixing methods are most applicable for hygromorphs with relatively thick active layers (above ~3 mm) due to the connections creating points of local stress concentrations, which can lead to cracking of wood veneer along the weaker longitudinal grain direction (Figure 3C). Thin wood veneer can still be coupled with perforated passive layers if the mechanical connections are replaced with a pattern of separate glued areas (spot-glued) to facilitate an improved distribution of the interfacial forces during the response (Figure 2, panel type 3).

The effects of the discussed material fabrication techniques on the responsiveness (magnitude of curvature changes) and reactivity (rate of curvature changes) of the resulting composites have been investigated in a lab test with controlled cyclic changes of ambient moisture conditions. Three samples of each of the four types of composites, listed in Figure 2, have been subjected to two successive cycles of wetting and drying and one cycle of ambient relative humidity (RH) change. In wet test stages, the samples were continuously sprayed with fine water mist, whereas in dry and humid stages, they were positioned in a room with ~40% RH and a climatic chamber pre-conditioned to ~85% RH, respectively. Constant temperature of around 25 °C was retained throughout the test. The duration of each test stage was sufficient for all samples to complete their response. The transition of the test conditions was purposefully abrupt in order to eliminate it as a factor affecting the response rate.

The response of the samples has been photographed with a DSLR camera at five minute intervals. Circular curvature (inverse of the curvature radius) has provided a good geometrical representation of their shape. The curvature has been determined from the photographs taken at selected time steps using transparent reference charts, placed between the samples as shown in Figure 4. This method is more laborious than automated data extraction based on digital coordinate tracking of marked sample parts, employed by Ruggeberg and Burgert [26], however, it enables simultaneous testing and direct performance comparison of multiple samples in equal conditions, which improves the consistency and validity of test results.

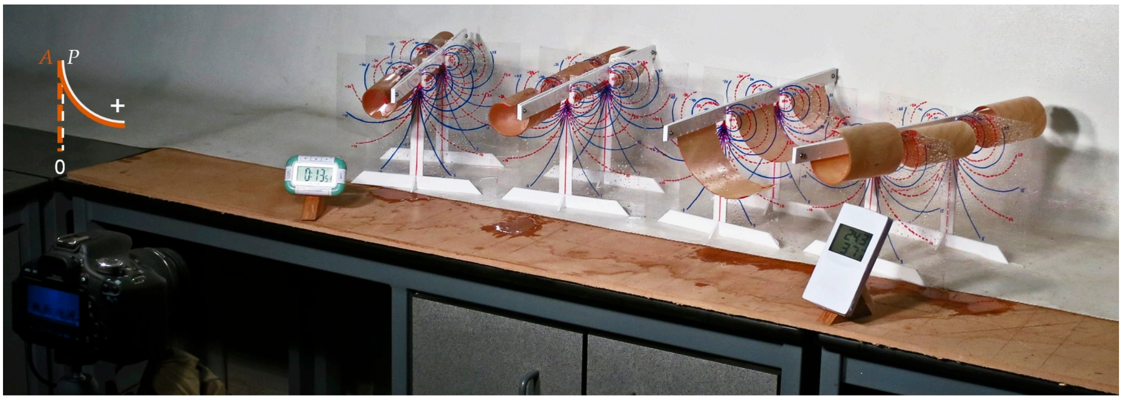

Figure 4. Experimental setup for lab-based tests on material reactivity to controlled wetting and drying and ambient relative humidity changes. Each sample stand accommodates three composite samples separated by transparent curvature reference charts. The sample stands are levelled with the camera and directed towards it to minimise the parallax effect, thus simplifying the curvature determination. The sign convention for circular curvature measurements, where "A" and "P" are active and passive layers respectively, is shown in the top left corner.

The results of the test have shown that spot-glued composites have the overall highest response speed among hygromorphs with analogous configurations and, owing to comparatively small amount of trapped water between the layers, they are noticeably quicker to dry from a wet state than hygromorphs with mechanical fixings (Figure 5). Similar to previous observations by Holstov et al. [34], all samples have responded significantly faster to wetting, where 80% of the total curvature change is achieved within the first 20–30 min depending on the composite type, than to ambient humidity changes, where the same proportion of the response takes 2–3 h. This is explained by the difference between quick initial adsorption of liquid water into wood dominated by capillary forces compared to much slower processes of molecular diffusion, evaporation and transport of water within the cell walls of the wood layer [21,33]. In addition, all composites exhibit a delayed response to drying after wet stages due to the initial evaporation of free water (stored in cell cavities) which does not influence the dimensional changes of the active layer.

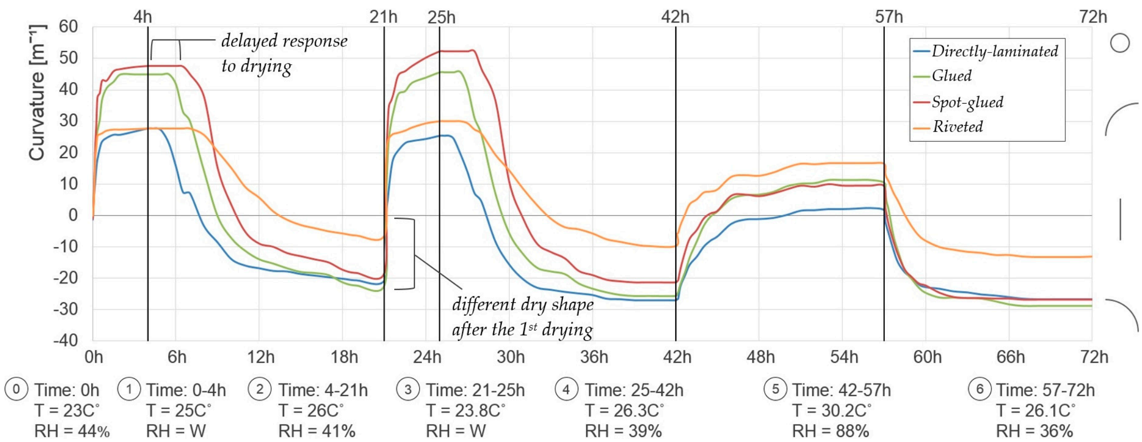

Figure 5. Average response of 150 mm long 100 mm wide samples of hygromorphs with four different types of layer bonding, but otherwise identical or analogous configurations, to cycles of wetting and drying and changeable ambient humidity. The tested composites consisted of 1 mm rotary-cut silver birch (*Betula pendula*) active layers and 0.2 mm rigid or 300 gsm laminated epoxy-glass passive layers. Full results of this test are provided in Supplementary Data File S1.

Pronounced differences between the total curvature ranges of the tested composite types indicate that the choice of material fabrication method affects both the speed and magnitude of the response. The reduced responsiveness of mechanically fixed and directly laminated composites results from local buckling of the active layer between the fixing points (Figure 3D) and differences between the stiffness of rigid and laminated epoxy-glass layers, respectively. Responsiveness of hygromorphs can be adjusted through selection of material configurations with different thickness, stiffness and hygroexpansion of the layers [34].

Identical hygromorphic composite configurations can be pre-programmed to exhibit response within different curvature ranges depending on application requirements (Figure 6). The pre-programming is applied during the material fabrication by pre-conditioning the wood to a specific moisture content, setting the initial shape of the composites, using pre-stressed layers or a combination of these methods. For example, hygromorphs with mechanically fixed layers can be pre-programmed to assume a straight shape in wet conditions if the MC during production of the active layer is equal to, or greater than, MCf and the layers are joined flat. Despite the inability to glue wet wood, the same pre-programming can be achieved with glued, spot-glued and directly laminated composites if the wood layers are pre-conditioned at high relative humidity and the materials are set into a slightly curved initial shape with the passive layer on the convex side (negative curvature). These pre-programming methods have been used for panels of prototypes "A" and "C" in Figure 7.

Whilst the composites prepared with saturated or nearly saturated active layers produce a consistent reversible response to cyclic wetting, drying and changeable ambient humidity, thin initially straight hygromorphs fabricated in room conditions exhibit a distinct difference between the first and subsequent response cycles returning to a reversed curved shape after the first drying (Figures 5 and 6). There is also a noticeable, albeit less pronounced, tendency for the response of these composites to shift towards a lower or more negative curvature with each consecutive response cycle. Conversely, it has been observed that hygromorphs with comparatively thick dry-bonded active layers (above ~5 mm) gradually obtain positive dry curvature after the first few wetting and drying cycles. This points to the possibility of selecting a "balanced" intermediate active layer thickness enabling a consistent cyclic response of dry-bonded hygromorphs. This principle has been employed when configuring the responsive panels, used for prototype "D" in Figure 7. Alternatively, the inconsistencies in the response of the thinner composites can be compensated by reducing the production MC of the active layer, preparing the composites with a positive initial curvature or using pre-tensioned passive or pre-compressed active layers. The first two of the above calibration methods have been used for pre-programming of the panels in prototype "B" in Figure 7.

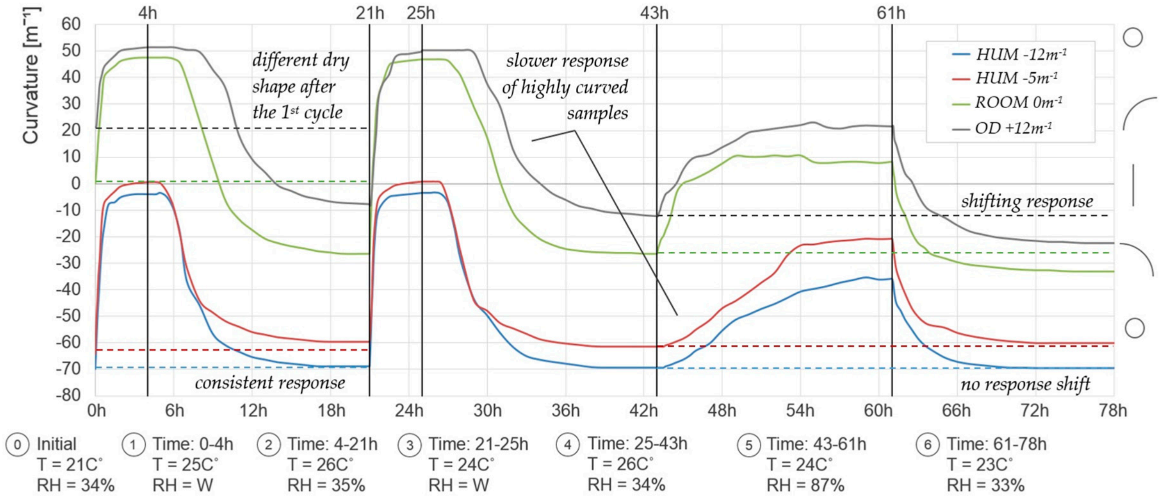

Figure 6. Average response of hygromorphic composite samples with different pre-programming, but identical dimensions and configurations (the same as glued composites in Figure 5). Different initial curvature and active layer pre-conditioning (where "HUM" is ~90% relative humidity (RH) at 23 °C, "ROOM" is ~35% RH at 23 °C and "OD" is oven-dried at 65 °C), have been applied for pre-programming. Same experimental setup and data collection methods have been employed as in the test described at the end of Section 2.1. Full results of this test are provided in Supplementary Data File S2.

2.2. Response Mechanisms and Cladding Configurations

Adjustment of the geometry and arrangement of hygromorphic composite panels and orientation of the layers and the direction of wood grain, allows transformation of local curvature changes of the materials into a range of more complex shape-morphing mechanisms involving different combinations of bending and twisting (Figure 1). The resulting movement can be employed to drive porosity changes of adaptive skins [39], actuate larger non-responsive elements [26], enable self-assembly of various constructs [27,41] and even power rotary or crawling locomotion [30]. The tunable and scalable response of the materials provides multiple opportunities for unique and creative designs of adaptive building skins with hygromorphic cladding.

The operational functionality of the responsive facades can be controlled both on material level and through design of cladding configurations and supporting understructure. Beyond aesthetic design considerations, the choice of cladding overlay pattern can influence the rate and degree of porosity changes [39] and enable additional functions, such as to prevent permeation of rainwater through the hygromorphic skin. The latter requires the clad surface to be inclined to set the direction of water flow and the cladding elements to be ordered and overlaid in such a manner that each panel overlaps the one below it, similar to wall shingles or roof tiling. Figure 7 shows two examples of possible cladding designs where the arrangement of overlapping composite panels, inspired by lizard skin ("A" and "B") and rectangular roof tiles ("C" and "D"), provides full surface coverage in pre-determined ambient conditions. Both of these designs are based on repeated patterns of identically sized panels facilitating simplified production.

In addition to testing of the developed cladding patterns and the ability to pre-program the response direction of hygromorphs, the prototypes have been used to further explore the effects of layer perforation on the response speed. The right side of each of the illustrated cladding modules contains panels with perforated top layers. In agreement with the test results summarized in Figure 5, the curvature change rate of thin spot-glued panels with perforated passive layers (in module "B") is approximately 30% higher than that of the glued panels without perforations. In contrast, since moisture is relatively quickly transferred across the small thickness of outside-faced veneer layers in panels of cladding module "A", the reactivity of these panels remains constant with active layer perforation or without. The response speed of the thicker panels in prototypes "C" and "D" is also not affected by additional perforation of either of the layers as moisture access throughout the composites is already enhanced due to bolted connection points.

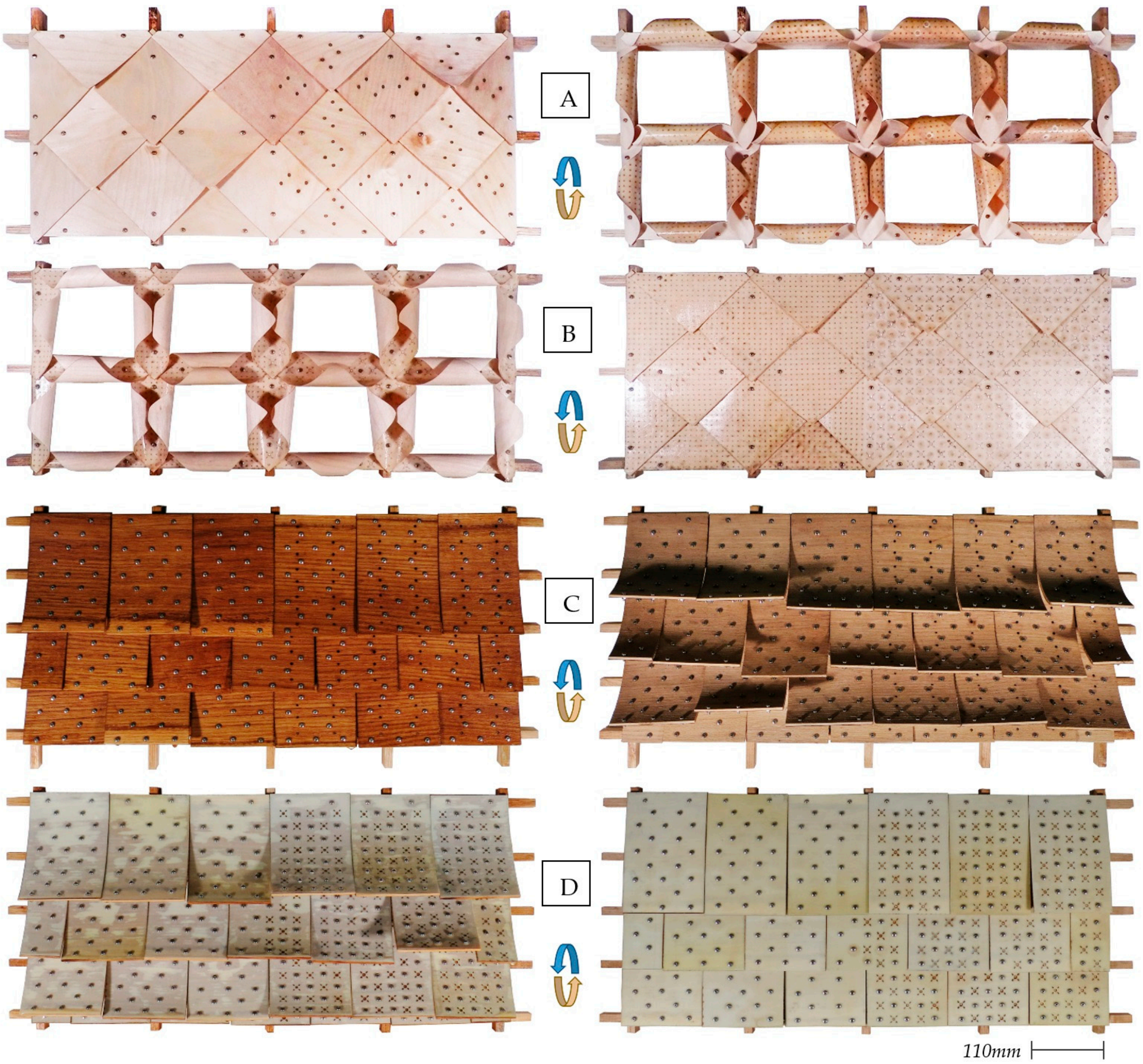

Figure 7. Prototypes of responsive cladding modules with different layer configurations and opposite pre-programming of panels in wet (left) and dry (right) conditions. The left and right sides of the prototypes consist of panels with standard and perforated active (**A**,**C**) and passive (**B**,**D**) layers, respectively. The configuration of thin panels (**A**,**B**) is the same as glued composites in Figure 5. Thick panels (**C**,**D**) comprise 3.2 mm thick quarter-cut English oak (*Quercus robur*) and 0.35 mm epoxy-glass layers.

The ability to control the response speed of thin composites through selective perforation of the passive layer has been employed to modify the cladding configuration with diamond-shaped responsive panels and improve its operational robustness, which is relied on the panels opening and closing in the correct order. The modified configuration, shown in Figure 9B, features perforated side panels ("B2") fixed along the vertical lines of the understructure and horizontal panels with spot-glued perforated top ("B1") and glued bottom halves ("B3") bending in opposite directions. The two-directional response is achieved by inverse arrangement of the layers in "B1" and "B3" (similar to Figure 1C). Different response direction and speed of the adjacent panels prevents them from clashing, while a high degree of porosity change during the response is maintained. The resistance of cladding with this configuration to excessive panel bending due to wind or snow load or imprecise pre-programming is also increased as four panels overlap in the middle of each opening and "B3" bends towards the tips of the other panels.

The reliance on sequential response of the overlapped panels can be eliminated if all panels within the diagonal checkerboard pattern have the top half bending down towards the understructure and bottom half bending up away from it, as shown in Figure 8C. Although the maximum porosity of the resulting cladding in the open state is somewhat reduced when compared to the configuration used for prototype in Figure 9B, this design has a number of key advantages including the ability to use a single type of cladding panels and apply passive layer perforation on both of their sides (Figure 8A) to maximise the response speed. In addition, unlike the prototype in Figure 9B, this panel arrangement provides separation between the edges of the adjacent panels in the open state. This prevents unwanted stresses caused by the interaction between the panels. Since the top corner of each composite panel is above the centre line of the adjacent panels due to overlapping, a simple linear understructure lattice (Figure 8B top) is not suitable for this cladding arrangement as it obstructs the movement of the composites. Figure 8B shows stages of development and optimization of the understructure design. The selected design (Figure 8B bottom) is based on a repeated pattern of uniform curves, which enables simplified cladding assembly.

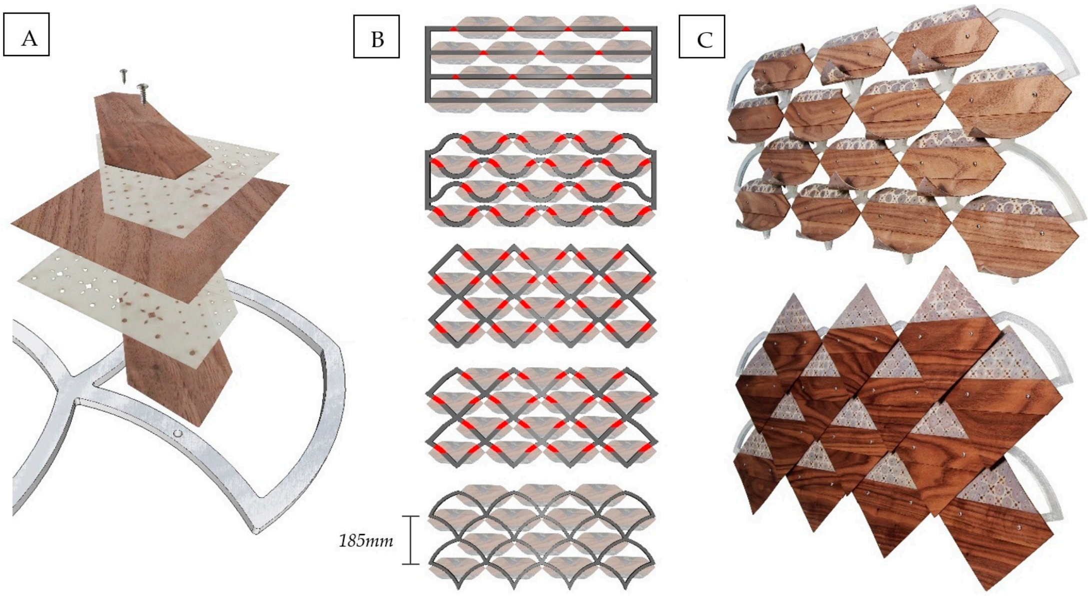

Figure 8. Prototype of hygromorphic cladding module incorporating identical overlapping composite panels (**A**) bending in two directions shown in dry/open and wet/closed states (**C**). A timelapse of the response is provided in Supplementary Video S3. The spot-glued panels consist of 0.6 mm black walnut (*Juglans nigra*) veneer and 0.2 mm thick epoxy-glass. The understructure (**B**) has been designed to prevent obstruction to the movement of the panels (red highlights) and maximise the resulting porosity changes. The chosen design (**B** bottom) is based on a repeated pattern of uniform curves reminiscent of fish scales.

2.3. Material Durability

Wood as a natural organic material is susceptible to biodegradation, particularly when exposed to warm humid environment, the conditions favourable for fungal growth. In nature, the balance between the rate of decay, which enables constant elimination of fallen trees and dead branches, and biosynthesis of wood in living trees is essential to preserve equilibrium in the ecosystem. A range of artificial preservative treatments are often applied to enhance the durability of man-made wooden products and structures and slow their degradation in challenging climatic conditions. However, the use of standard wood protection methods, including a variety of surface coatings and impregnated chemicals, results in reduced hygroscopicity of wood [35,47–49]. This normally advantageous side-effect renders these methods unsuitable for hygromorphic wood composites, which require the exchange of moisture between the active wooden layer and ambient climate to drive their response. Small thickness of the composites and the stresses which result from their repeated response and interaction between the shape-shifting cladding panels present further challenges for their long-term durability even when compared to unprotected sawn wood alone.

Previous research on hygromorphs has mainly involved short-term tests of their responsive properties in controlled laboratory environment [19,34]. Two longer-term studies have included two-year-long testing of hygromorphic panels in an enclosed transparent container, protecting the materials from direct exposure to the elements, whilst permitting their reaction to outdoor relative humidity changes, [39] and a nine-month-long outdoor test of small scale hygromorphic actuators [26]. Despite the use of samples with inherently non-durable active layers, including sycamore maple (*Acer pseudoplatanus*), European beech (*Fagus sylvatica*) and Norway spruce (*Picea abies*) [50], neither of these tests have been long enough to result in significant loss of responsive capacity of the materials. The existing studies provide limited insight into the longer-term effects of degradation on visual aging and mechanical wear of hygromorphic cladding panels and are insufficient to assess the usability lifespan of the materials.

One-year-long outdoor testing of hygromorphic cladding modules and material samples has been conducted to explore the durability of the composites in full weathering conditions, test their response speed to natural weather patterns and evaluate the performance of the developed panel arrangements. Long-term field tests have been chosen over accelerated cyclic lab tests due to the inability of artificially recreating the simultaneous effects of multiple degradation factors present in the natural outdoor environment, such as precipitation, UV radiation, biological decay, wind and snow loading and mechanical erosion. The responsive cladding modules, shown in Figure 7C,D and Figure 9B, and twenty-four 50 mm $\times$ 125 mm glued composite samples with four different material configurations and two opposite types of pre-programming (details of the material configurations are given in Supplementary Data File S4) have been mounted onto a triangular wooden frame, placed on a flat building roof (Figure 9A). The condition of each sample and selected panels of the responsive cladding modules has been assessed weekly based on the extent of layer delamination, fungi-induced degradation, mechanical decomposition, cracking, discolouration and staining of the layers. The changes in the responsive capacity of the composites have also been monitored throughout the test by taking their wet shape, measured at least once every month, as a reference point. The test methods and degradation assessment reference criteria (described in Supplementary Data File S4) have been developed using the existing recommended procedures for experimental evaluation of wood durability [51], modified for the use with composites. Visual assessment methods have been adopted due to the impracticality of gravimetric measurements of comparatively small lightweight panels, which would have to be regularly removed and reattached to the understructure. Although less subjective than visual assessment, photographic analysis could not be used because of changeable shape of the panels. Destructive testing methods, such as pick or splinter tests [52], had to also be avoided due to the need to preserve the integrity of the samples and enable their continued response function.

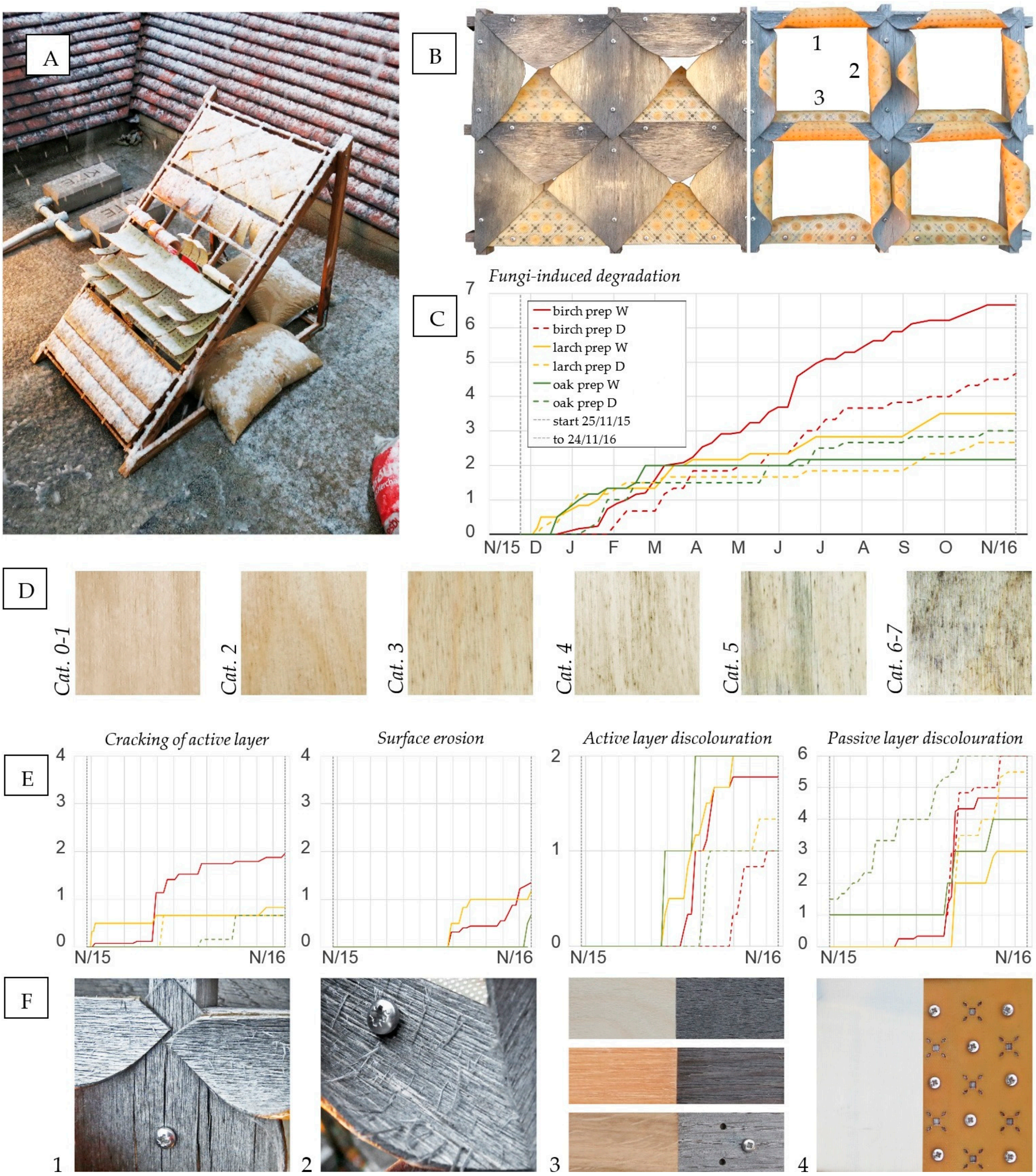

Figure 9. (**A**) Outdoor testing prototype incorporating hygromorphic panels and samples with different material configurations and pre-programming; (**B**) responsive cladding module with improved arrangement of panels in wet/closed and dry/open state after 12 months in full weathering conditions; (**C**) time plot of fungi-induced degradation, where "prep D" and "prep W" are composites pre-programmed to assume flat shape in dry and wet conditions, respectively; (**D**) illustration of the fungi-induced degradation categories from (**C**); (**E**) time plot of other effects of degradation, including (from left to right) average sample cracking, mechanical decomposition and active and passive layer colour changes (use the key from (**C**)); and (**F**) illustration of the material degradation effects from (**E**) in the same order. Full test results and description of the assessment categories for the degradation effects plotted in (**C**,**E**) are given in Supplementary Data File S4.

The key results of the durability study have been plotted in Figure 9C,E with examples of the identified degradation effects illustrated in "B", "D" and "F". No delamination of the composites beyond the initial minor damage to the interlayer bond of several glued panels, incurred during material production, has been observed. Despite frequent high winds characteristic to the North East of England and some particularly windy days during storm Eva in December 2015 and storm Angus in November 2016 with the speed of wind gusts exceeding 25 m/s [53,54], none of the panels and samples have become damaged or detached from the understructure. The composites have also been able to withstand a minor snow coverage of up to 20 mm without noticeable effects on their pre-programmed shape. However, several signs of mechanical material degradation have progressively become apparent, particularly on thin responsive panels with silver birch active layers. The first of these signs has been the formation of cracks along the grain of the veneer layers near the panel fixing points (Figure 9(F1)). The cracks, caused by the pressure from the adjacent panels and uneven drying of the composites, have started appearing around four months into the test, when gradual proliferation of mould and incipient photo-degradation of lignin (the material bonding wood cells and cell components together) in the surface layers of wood have begun affecting its tensile strength [47,49].

The UV-induced lignin decomposition has intensified during the summer months due to increased daily solar irradiation. This has resulted in an onset of surface erosion (Figure 9(F2)) on panels with wood layers on top ("prep W") after nine months from the start of the test—around the same time as the first changes in the responsiveness of these panels have been observed. On average, untreated wood can lose about 0.5 mm of thickness per decade due to weathering and abrasion by airborne particles of dust and sand [33,47,49]. This makes surface erosion a significant factor of thin composite degradation. By the end of the one-year-long test, the curvature range of the composites with outside-faced 1 mm thick birch active layers had been reduced by around 10% leading to a visually distinguishable deviation of the panels from a completely flat shape in wet state (Figure 9B). Other tested composites with the same pre-programming have been less affected by the surface erosion due to larger thickness of their active layers. Hence, their responsive capacity has remained constant (Supplementary Videos S5 and S6). No signs of wood cell erosion have been spotted on the samples and panels with passive layers on top, owing to comparatively limited exposure of their active layers to direct sunlight in dry weather. The effects of fungal attack on these panels have also been less profound, due to their up-bent wet shape preventing accumulation of rainwater on the surface of the active layer. However, the resistance of the composites to moulding has been most significantly influenced by natural durability of the selected wood species determined by the content of toxic phenolic extractives [47,49,52]. Consequently, while hygromorphs with active layers made of naturally durable English oak and European larch heartwood have become covered with relatively sparse and small mould patches that have not greatly affected their appearance, the composites with perishable birch veneer layers have been impacted much more severely. Other effects of visual aging have included discolouration of the wooden layers (Figure 9(F3)) caused by gradual leakage of extractives and removal of lignin [47,49] and UV-induced yellowing of the epoxy matrix in fiberglass (Figure 9(F4)). As seen from the diagrams in Figure 9E (middle-right and right), these changes have always been more pronounced in the layers of the composites positioned on top.

The observed degradation rates suggest a projected usability lifespan of around one year for hygromorphs with perishable wood layers used outside. The thicker composites with naturally durable layers should be able to withstand the challenging outdoor weather conditions for two years or above without significant changes of their responsive capacity. Substantially improved longevity of the materials can be expected if they are protected from wetting or deployed indoors, thus preventing the moisture content from rising above MCf [21] in order to avoid optimal conditions for fungal growth and issues associated with slow uneven drying. Visual aging of untreated wooden layers is inevitable within the first year of the use outside. However, the changes are not necessarily deleterious to the aesthetic appeal of the composites as long as the fungal growth is not too apparent. In fact, the natural silvery-grey look of aged wood is often considered attractive and is the reason why certain wood species naturally-resistant to fungal growth are sometimes left untreated and unfinished [55]. Similarly, the inherent variability of wood properties, leading to a perceptible divergence between the response of identically configured composites, can in fact enhance the subjective enjoyment of hygromorphic skins by emphasising their similarity with natural living organisms.

3. Sustainable Materialisations

3.1. Synchronised Climate-Responsiveness

Continuous monthly interval photography of the outdoor testing prototype paired with simultaneous measurements of weather data have been used to assess the degree of synchronisation between the dynamic behaviour of the materials and natural variable rhythms of local outdoor climate in Newcastle upon Tyne, UK. Changes in ambient relative humidity and direct contact with condensed or precipitated moisture are the main climatic stimuli for response of hygromorphs, but the rates of moisture exchange between the active wooden layers and ambient environment are also influenced by air temperature, solar irradiation and wind speed. The thinner hygromorphic panels and samples have demonstrated an ability to react swiftly to sporadic short-term precipitation and follow repeated diurnal cycles of humidity changes, which are most pronounced in the summer months when the average difference between humidity at night (higher) and during the day can reach 25%. Increased relative humidity before rain initiates transformation of the responsive cladding in advance. This preliminary response can benefit applications that require a quick formation of a rainproof barrier (Figure 10A). Among other factors, the response rate to relative humidity is affected by curvature of the composites (Figure 6) as twisted panels can physically confine the active layers. Slower response of the thicker panels allows adherence to longer-term relative humidity patterns, with full response only occurring during prolonged periods of precipitation or drought. In the North East of England, where the average relative humidity during the winter months approaches 90% and frequency of rainy days is similar across different seasons, the thicker composites may only achieve their dry shape during several continuously dry weeks in summer.

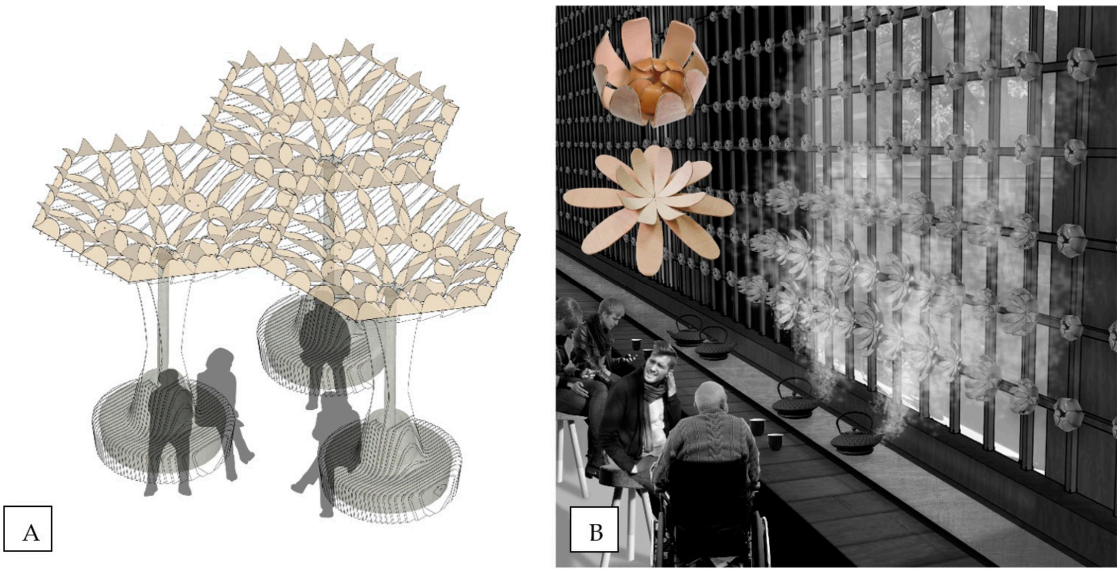

Figure 10. (**A**) Design concept of modular outdoor seating with a responsive canopy roof and an integrated drainage and rainwater collection system; and (**B**) artistic render of a teahouse with interior wall cladding comprised of responsive elements designed to imitate opening and closing of tea-flowers.

Based on our developing understanding of the responsive characteristics of hygromorphic wood composites, we have begun to identify and speculate on opportunities for their application in environmentally responsive building design [34]. The weather dependant behaviour of hygromorphs predisposes their climate- and region-specific applications and we have been exploring varied and novel potential use scenarios of different material specifications beyond adaptive façade cladding through design work that integrates postgraduate students in both Architecture and Engineering at Newcastle University. For instance, thick composites with slow gradual response can be applied in climates with distinct rainy seasons, such as San Francisco, US and Jakarta, Indonesia [56], for large landscape scale flood warning and alleviation. Thin composites with higher response rate and curvature changes can be deployed in a range of indoor adaptive systems responding to building occupancy and use, such as increased humidity during public gatherings or resulting from cooking or showering (Figure 10B).

3.2. A Typology of Applications

The continuing development of hygromorphic shape-changing materials will open up new applications and design possibilities not yet considered, with opportunities for corresponding changes in quality of life, material sustainability and environmental benefits [57]. It is this multi-dimensional character of hygromorphic technologies that particularly interests us as they offer opportunities to extend the accepted and conventional definition of what constitutes sustainable materiality within architectural design. The possibilities for varied and integrative design applications provide for the merging of competing and often contradictory demands that are placed on building technologies within environmentally responsive and adaptive architectures. Hygromorphic material systems could therefore enable simultaneously addressing a wide range of sustainability considerations [34] that go beyond energy efficiency and embody the concerns of human comfort, ecological aesthetics and local relevance. One of the fundamental challenges for the future development and building integration of hygromorphic wood composites is in speculating on, understanding and then exploiting the full potential of the technology to address this expanded range of design criteria and applications. A review of current research and literature would suggest a hierarchy of four overlapping typologies of application within architectural design:

(1) Functional devices/components (actuators, micro-generators, sensors, locomotion engines etc.);
(2) Performance-oriented adaptive systems (enhanced occupant comfort, energy efficiency etc.);
(3) Formal/aesthetic/spatial experience value (enhanced visual appearance of dynamic facades);
(4) Contextual/location-specific value (buildings as a physical representation of local environment and climate).

1. The simplest level of application for hygromorphic composites is as discreet functional devices where the main design challenge is in integrating and combining the materials with other technologies and building components. As we progress through the hierarchy of applications to those that impact on the building envelope, human comfort, spatial or formal experience and aesthetics, the extent and demands on the technology and on the need for wider building integration increase substantially. Here we focus on the challenges of these complex and highly integrated applications, which have an inherent requirement for interdisciplinary design methods and approaches.

2. The integration of adaptive and kinetic façade systems that enable adjustment and self-optimisation of building properties in response to ambient climatic conditions can help shift the role of the building envelope from an environmental barrier towards an environmental mediator [1] that exploits rather than blocks the effects of natural heating, cooling and light to continuously maintain occupant comfort whilst reducing the demand for the use of conventional active building systems. The application of materials with intrinsic sensitivity to climatic stimuli can serve as an underpinning principle for development of simpler, yet more versatile adaptive building skins with passive embedded response.

3. One of the most interesting and engaging aspects of hygromorphic materials are the striking visual effects that can be achieved through their design integration coupled with their shape-changing and adaptive behaviour. The biomorphic expressiveness of hygromorphs relates to what Guy and Farmer [58] (p. 143) have referred to as “eco-aesthetics”, an environmental design approach that

promotes biomimetic architectural forms where the formal, aesthetic and sensual values of buildings are considered just as important to sustainable architecture as reduced energy consumption or ecological footprint. Within this design logic there is an emphasis on architectural forms that mimic nature and in doing so celebrate the wider environmental problem of how we relate to, and interpret nature. The prototypes built by Achim Menges and his colleagues at Stuttgart University including "Hygroscope" art gallery installation and "FAZ" and "Hydroskin" temporary pavilions, embed this approach and demonstrate that integration of hygromorphic materials provides opportunities for what Menges terms a "unique convergence of environmental and spatial experience." [13] (p. 58). In these aesthetically driven applications, there is an emphasis on creating a dramatic ecologically-embedded architecture where "the perception of the delicate, locally varied and ever-changing environmental dynamics is intensified through the subtle and silent and silent movement of the responsive envelope" [13] (p. 58).

4. According to Guy and Farmer [58] (p. 144), one of the key threads in contemporary environmental discourse around sustainable architecture is an emphasis on developing buildings that are both designed to be grounded in their site and fully expressive of the characteristics of their location. This approach emphasises a fundamental concern for authenticity and the notion that truly sustainable buildings need to more fully relate to the concept of locality and place. Sustainability means adapting to, and living within the constraints and possibilities imposed by the characteristics of a particular region. "Universal" technological solutions are considered unsustainable because they often fail to coincide with the particular values of a place or people. The application of hygromorphic materials requires that designers make technical decisions which are based on an understanding of site as well as developing a place-specific design strategy that acknowledges the importance of the local climate as a key constituent and driver of the material application. In this sense, the continuous response of hygromorphs provides for a unique ability to adapt to and reflect the particular local ecological conditions and weather patterns. An interesting example of hygromorphic materials deployed to both relate to, and to express very particular site conditions is Jason Payne's proposals for Raspberry Fields in Round Valley, Utah [59]. This proposed renovation of an existing, one-room schoolhouse is a sensitive response to the differential weathering patterns found on the existing timber shingle cladding, which varies on each building elevation depending on orientation to the sun and prevailing winds. The proposed design seeks to utilise the hygromorphic response of newly added, inversely hung timber shingles to emphasise and amplify the expression of these existing weathering patterns. This project exemplifies an innovative construction approach that borrows from the established techniques of the existing vernacular buildings of the area. The building is therefore conceived as an expression of both the local climate, through the deployment of the natural hygromorphic behaviour of timber cladding, and design traditions.

The next step in our research work is to develop some of these ideas for place-based applications of hygromorphs through their monitored integration into a permanent observatory building for nature and bird-watching in the Kielder Forest, Northumberland, UK (Figure 11). To our knowledge, this will be the first permanent application of building integrated hygromorphic wood composites. The Kielder Forest is a large forestry plantation in Northumberland and is the largest man-made woodland in England. It was planted to provide the UK with a sustainable source of constructional timber. Kielder is dominated by conifers and the main species in the forest are spruce, pine, fir and larch. The use of hygromorphs in this particular project has been inspired by the proliferation of pine cones at the site and influenced by the relevance of hygromorphic materials to the locality as well as the wishes of the client (Kielder Water and Forest Park Trust) to deploy them as a means to educate visitors about the immediate environment. This project will not only allow to test the real-world practical viability of hygromorphic systems but also to gauge and ascertain the reception and understanding of the materials on behalf of visitors and users within the local ecological context.

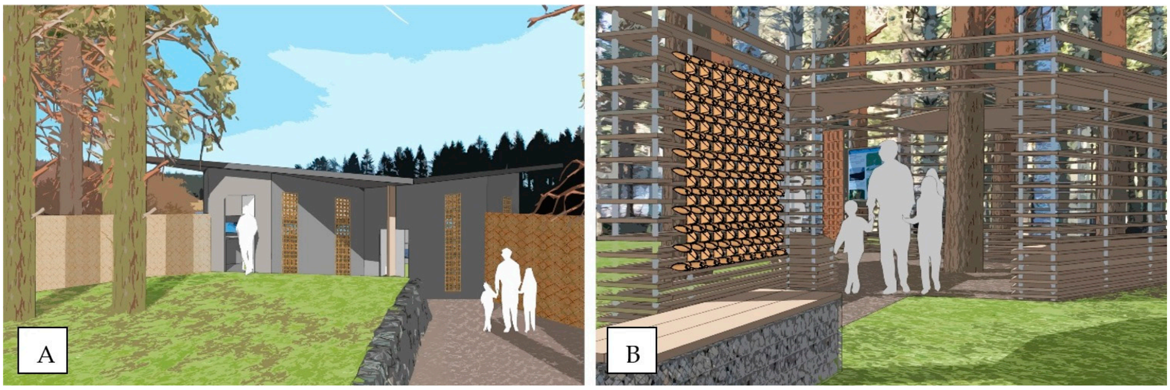

Figure 11. Concept drawings of bird hide pavilion (**A**) and "welcome point" (**B**), its outdoor reception area.

4. Conclusions and Recommendations for Future Research

Over the last 20 years, the research on biomimetic moisture-responsive composites has advanced rapidly from the identification of the opening mechanism of pine cones in 1997 [20], the development of man-made bilayer responsive materials [19,22] in 2009, and more recently widespread research into synthetic hygromorphs [23,27–30] and tentative steps towards application [26,27,39]. Within existing published work, details of fabrication techniques, material response over multiple cycles, durability, and response to external weathering are scarce and we have sought to address this gap in available knowledge.

For the first time, the results of long-term outdoor field testing of wood-based hygromorphic cladding have been reported. Overall, the panels performed extremely well with minimal delamination and no cracking or breakage despite exposure to wind and many cycles of wetting and drying on an exposed roof in Newcastle upon Tyne, UK. The role of fabrication methods in ensuring durability and correctly programmed, repeatable behaviour has been described, and the results of long-term field testing have helped establish the significance of different degradation factors and provide an estimate of the expected lifespan of the materials. Whilst biodegradability reduces the environmental impact of hygromorphic wood composites at end of life, it also affects their durability and longevity. The panels may need to be replaced more regularly than conventional cladding, increasing maintenance requirements. Mechanical fixing enables panels to be deconstructed, damaged layers to be replaced, and "technical and biological nutrients" to be separated at end of life for effective recycling [60]. Further long-term full-scale field testing, coupled to multiple-cycle lab tests and numerical simulation of stresses within the bilayer composites, should enable panels to be developed with enhanced functional longevity.

Beyond technical considerations, we have started to explore the potential functional and aesthetic benefits of hygromorphs wood composites in adaptive architecture. The ability to create building elements which passively respond to the local climate and weather conditions, at timescales varying from a few minutes (thin panels responding to rain and diurnal humidity cycles) to monthly or annual (thicker panels responding to seasonal humidity changes and average rainfall), provides new opportunities for sustainable responsive architecture. Whilst the case study described here is in a remote, natural location with obvious benefits of using "low-tech" wood-based cladding, there is also potential for these materials to form part of the burgeoning "living architecture" movement [61], where they could provide climate-responsive elements alongside green roofs and green walls within modern, dense urban environments.

Supplementary Materials: The following are available online at www.mdpi.com/2071-1050/9/3/435/s1. Excel Spreadsheet S1: Test of composite samples with different types of layer bond, Excel Spreadsheet S2: Test of composite samples with different pre-programming, Video S3: Closing and opening of prototype with two-directional panel response, Excel Spreadsheet S4: Long-term outdoor test data, Video S5: Outdoor testing timelapse (initial), Video S6: Outdoor testing timelapse (after 12 months).

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Conflicts of Interest: The authors declare no conflict of interest.

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